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A Methodology to Assess the Best Estimate Trajectory (BET) Results Generated for the Kwajalein Missile Range

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The SBIR Phase I final report included herein pertains to topic number A90-443, entitled Trajectory Estimation, of Program Solicitation 90.2. The primary objective of this study is the creation of a methodology whereby more realistic assessments of the aerodynamic forces acting upon reentry vehicles flown from the U.S. West Coast to the Kwajalein Missile Range (KMR) are obtained. This proposed methodology is based on a compilation of various sources of information into a knowledge base. These data would include trajectory estimates via all available post-flight Best Estimate Trajectory (BET) sources, associated data from radar and optical tracking sites, and information from atmospheric models and measurements. Additionally, this database will incorporate telemetered on-board sensor measurements when available. As a result, a knowledge base would exist including historical and future-generated data to be utilized for detailed statistical assessments of the aerodynamic and atmospheric issues effecting reentry vehicles. These findings could then be implemented in the various trajectory fitting

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processes by enhancing the subsequent modeling of these critical forces. Also, this report discusses, and recommends the use of, a BET methodology to support a limited set of reentry vehicle tests which utilize on-board instrumentation. These results would provide another set of valuable data to be included in the database analyses implied above. Moreover, this BET generation process is proposed herein as the primary contributor for a KMR tracking sensor study. This activity would include a NASA Space Shuttle entry trajectory reconstruction by employing support from various tracking complexes. Hence, an excellent opportunity would exist to provide detailed statistical assessments of the KMR external sensors in the launch, mid-range, and terminal areas.

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LIST OF ACRONYMS, SYMBOLS, AND SUBSCRIPTS

ADDB	Aerodynamic Design Data Book
AF'78	1978 Air Force Reference Atmospheres
AFE	NASA Aeroassist Flight Experiment
AFFTC	Air Force Flight Test Center
ALCOR	ARPA-Lincoln C-band Observables Radar
ALTAIR	ARPA Long-Range Tracking, Acquisition, and Instrumentation Radar

LIST OF ACRONYMS, SYMBOLS, AND SUBSCRIPTS (continued)

ARPA	Advanced Research Projects Agency
BCS	Boeing Computer Services
BET	Best Estimate Trajectory
c_s	speed of sound
C_N	normal force coefficient
C_{Np}	predicted normal force coefficient
c.g.	center-of-gravity
c.p.	center-of-pressure
CDC	Control Data Corporation
CFD	computational fluid dynamics
DFRC	Dryden Flight Research Center
DoD	Department of Defense
EAFB	Edwards Air Force Base
EAFC	FPS-16 C-band radar at EAFB
EFFC	FPS-16 C-band radar at EAFB
EI	entry interface
ENTREE	Entry Trajectory Estimation Program
FAD	Flight Assessment Deltas
FM&C	Flight Mechanics & Control, Inc.
FRCC	FPS-16 C-band radar at NASA DFRC
g	gravitational acceleration
GFE	government-furnished equipment
GMT	Greenwich Mean Time
GRAM	MSFC Global Reference Atmospheric Model
GSFC	Goddard Space Flight Center
GSTDN	Ground Spacecraft Tracking and Data Network
h	altitude
HAIR	High Accuracy Instrumentation Radar
JSC	Johnson Space Center
km	kilometers
KMAC	P-band ALTAIR radar at Kwajalein
KMLC	P-band ALTAIR radar at Kwajalein
KMR	Kwajalein Missile Range
KMRC	C-band ALCOR radar at Kwajalein
KMTC	FPQ-19 C-band radar at Kwajalein
KPTC	FPQ-14 C-band radar at Kaena Point, Hawaii
KSA	Kwajalein Standard Atmosphere
L/D	lift-to-drag ratio
LaRC	Langley Research Center
M_R	Mach number based on V_R
m	spacecraft mass

LIST OF ACRONYMS, SYMBOLS, AND SUBSCRIPTS (continued)

MSFC	Marshall Space Flight Center
N	Newtons
NASA	National Aeronautics and Space Administration
NOS	Network Operating System
NWS	National Weather Service
P	atmospheric pressure
PC	personal computer
PHL	Preliminary Hazard List
PMFC	FPS-16 C-band radar at Point Mugu, California
PMPC	FPS-16 C-band radar at Point Mugu, California
PMSC	FPS-16 C-band radar at Point Mugu, California
PPMC	MPS-36 C-band radar at Point Pillar, California
PTPC	FPQ-6 C-band radar at Point Pillar, California
q	dynamic pressure
R^*	universal gas constant
RCS	reaction control system
RIM	Relational Information Manager
RV	reentry vehicle
S_{ref}	aerodynamic reference area
SBIR	Small Business Innovative Research
SNFC	FPS-16 C-band radar on San Nicholas Island
SNIC	FPS-16 C-band radar on San Nicholas Island
SNSC	FPS-16 C-band radar on San Nicholas Island
STS	Space Transportation System
T	atmospheric temperature
TBD	to be determined
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
U.S.	United States
USASDC	U.S. Army Strategic Defense Command
V_R	planet-relative velocity
VAFB	Vandenburg Air Force Base
VDBC	TPQ-18 C-band radar at VAFB
VDFC	FPS-16 C-band radar at VAFB
VDHC	C-band HAIR radar at VAFB
VDSC	FPS-16 C-band radar at VAFB

LIST OF ACRONYMS, SYMBOLS, AND SUBSCRIPTS (concluded)

GREEK SYMBOLS

γ	ratio of specific heats
μ	mean value
μ	molecular weight
ρ	atmospheric density
ρ_{C_N}	C_N Shuttle-derived density
σ	standard deviation

SUBSCRIPTS

A	air-relative
N	normal
p	predicted
R	planet-relative

I. TECHNICAL SUMMARY ABSTRACT

The generation of a BET is part of the post-flight assessment of test vehicles flown to the Kwajalein Missile Range (KMR). This process is performed by statistically fitting a single trajectory through all of the available external tracking data. These data are weighted by the a priori knowledge of their measurement accuracies and, typically, fixed biases are estimated and removed during the trajectory fitting process. Also, for some flight test vehicles, on-board sensor data may be available post-flight to assist in vehicle state prediction during the trajectory reconstruction activity. Similar to the external sensor data, these on-board measurements can also be rectified for biases, scale factors, and misalignments that may be determined. These in situ measurements are extremely useful in making the BET generation process *atmosphere independent*. Unfortunately, these data are not always available. An inherent problem in the trajectory estimation process, specifically when on-board sensor data are not available, occurs during gaps in external sensor coverage. Here, results in these regions have indicated that vehicle maneuvers are implied that are not physically realizable. This problem has been shown to be even more critical near the terminal area at the KMR where sensor coverage ends above the region of impact.

The development of more elaborate aerodynamic models for the entry segment is fallible and may not resolve the anomaly described above. FM&C has investigated the feasibility of addressing this problem via a knowledge base compiled from existing (and future) data. Data would be included from all available BET sources, associated radar and optical tracking sites, atmospheric models and measurements, and, if available, telemetered on-board sensor measurements. This knowledge base would be compiled from a series of flight tests to ensure a representative statistical sample. Thus, a database consisting of readily available historical and future generated results would be utilized to provide detailed statistical assessments of the critical aerodynamic and atmospheric issues implied above. For example, a study of the lift and drag forces on a reentry vehicle could be performed by compiling results from all BET sources for several flights. A more comprehensive statistical analysis would then exist to address the expected deviations of these parameters from a nominal ballistic trajectory and, thus, enhancing the subsequent modeling of same.

Additionally, FM&C has investigated the use of its own BET methodology in support of flight tests with instrumented vehicles. This would be another valuable source of post-flight BET data for inclusion in the aforementioned database analyses. As indicated, this methodology relies on a source of dynamic data (i.e., accelerometer and rate gyro data) for the vehicle. Furthermore, FM&C has proposed a joint Space Shuttle entry trajectory reconstruction activity employing KMR tracking support. By utilizing the Shuttle tracking network in conjunction with typical radar and optical tracking data used in KMR tests, an excellent opportunity exists to provide detailed assessments of these external sensors.

II. INTRODUCTION

The post-flight assessment of reentry test vehicles flown from the United States west coast to the Kwajalein Missile Range (KMR) includes an accurate determination of the vehicle's trajectory. This flight path history of a reentry vehicle (RV) is typically generated via the so-called Best Estimate Trajectory (BET). A BET is produced from a statistical estimation process whereby a single, "best" trajectory is fit through all the available sensor data. These measurements may include data from on-board and/or off-board sensors. On-board sensors typically include linear accelerometers to provide measurements of vehicle acceleration and rate gyros to provide vehicle attitude information. Data from these sensors may either be telemetered during a RV test flight, or recorded on-board for later processing if the vehicle is retrievable. It should be noted that the number of instrumented vehicles such as these are limited during a series of flight tests.

Off-board sensors include tracking data provided by various complexes in the launch, mid-range, and terminal areas during a flight test. Data from these sensors typically consist of range, azimuth, and elevation measurements from C-band radars, very accurate measurements of azimuth and elevation angles from camera data (i.e., Radot, Super Radot, etc.), and, if available, surveyed impact data in the terminal region. C-band coverage for RV tests is normally provided via beacon tracking as opposed to skin tracking with which some readers may be more familiar. These various sets of tracking data provide the external reference to which the vehicle's trajectory is statistically "fit" during the BET process.

Two (2) basic methods can be employed to generate the trajectory for an entry vehicle in the Earth's atmosphere. These consist of numerical solutions to the governing equations of motion or deterministic integration of vehicle dynamic data. For the latter, if on-board sensor data are available, measurements of vehicle acceleration and attitude are utilized during the state (and attitude) prediction process. It is important to note that these *in situ* measurements are extremely useful in making the BET generation process *atmosphere independent*. Here, these measurements replace the force and moment modeling normally included in the vehicle's governing equations of motion. During this propagation scheme, various instrument errors such as fixed gyro drifts, scale factor errors, and misalignments can be determined and rectified if deemed necessary. By applying the previously mentioned tracking data as an external reference, the vehicle's initial state is updated and the state prediction process repeated. Additionally, the tracking data are typically weighted by the known accuracies of the various sensors and, if needed, fixed biases can also be determined and removed. By utilizing this iterative scheme, the so-called observation residuals (observed tracking data minus the computed measurements) are minimized, and the final trajectory (i.e., the BET) is obtained.

Here, readers should note that various statistical processing methods are available to include Kalman filtering techniques and least-squares batch processors.

If on-board instrumentation data are not available for the BET generation process, then vehicle state prediction relies solely on the mathematical modeling of external forces and moments within the governing equations of motion. This process is readily applied in orbit determination analyses for orbiting spacecraft, but becomes inherently complex for RVs entering appreciable Earth atmosphere. This region is typically defined at altitudes below 91 km (300,000 feet). As supplemental information, it should also be noted that radar and/or optical tracking data can be utilized to determine the state of a reentry vehicle. Here, velocity information is obtained by numerically differentiating these position data. This method, though, is not practical in that it requires continuous tracking coverage, yields no vehicle attitude information, and can produce erroneous results in the velocity determination.

Currently, aerodynamic models for reentry test vehicles are limited to smooth, slender vehicles with symmetric mass distribution where the center-of-pressure (c.p.) coincides with the center-of-gravity (c.g.). This, of course, is the simplest form of the model but, readers should note, is still quite complex. Six (6) aerodynamic coefficients are normally modeled here to include three (3) force coefficients of drag, side, and lift, and three (3) *moment* coefficients of roll, pitch, and yaw describing the aerodynamic torques on the RV. Interested readers can find a more detailed description of these models in Reference 1.

Current BET results have shown that, for non-instrumented flight test vehicles, maneuvers are being estimated during atmospheric entry that are not physically realizable. These results are especially poor during periods when the RV is crossing gaps between successive tracking sensors. These tracking gaps have been further isolated to those occuring between the end of radar and optical coverage, where data quality degrades due to high refraction gradients and radar multipath, and the surveyed impact location. As a result of these discrepancies, a more realistic assessment of the aerodynamic forces acting on the vehicle, and the effects due to these forces, are desired to be included within the BET process.

Based on a historical perspective, it has been determined that the development of more elaborate aerodynamic models for the entry segment is, in itself, an unreliable procedure and may not solve the problems encountered thus far. This is due to the inherent complexities associated with reentry aerodynamic phenomena for even a simple vehicle as described above. For more aerodynamically complex vehicles such as a lifting body concept, these problems become even more severe as one would expect. Additionally, the uncertainties associated with the surrounding atmospheric environment provides another source of error. As a result of these observations, an aerodynamic modeling task of this nature could become both time-consuming and counter-productive.

Flight Mechanics & Control, Inc. (FM&C), under contract DASG60-91-C-0024 to the U.S. Army Strategic Defense Command (USASDC) in Huntsville, was tasked to investigate solutions to these types of problems. The work presented here was performed via Phase I funding from the Small Business Innovative Research (SBIR) program during a six (6) month period of performance. This final report is a comprehensive document describing proposed recommendations for assessing the aforementioned trajectory estimation anomalies, and, ultimately, will lead to a SBIR Phase II proposal for follow-on funding. The results of this investigation are based on extensive studies of the feasibility of several approaches whereby beneficial conclusions can be drawn to address these problems.

As opposed to developing more complex aerodynamic models describing the atmospheric entry portion of an RV flight, FM&C analysts are proposing the compilation of a knowledge base consisting of both historical and future post-flight data to assess these trajectory determination discrepancies. This database would be composed of information from various BET sources to include their respective trajectory estimates, associated radar and optical tracking data, and, whenever available, telemetered sensor measurements from on-board instrumentation. It is also recommended that this knowledge base be divided for each class of test vehicle to ensure commonality of results. Hence, a database would then exist that could be utilized to investigate the important aerodynamic (and atmospheric) issues effecting a reentry vehicle. These analyses would be performed as detailed statistical assessments utilizing an ensemble of data over many flights. For example, a statistical spread of maximum lift and drag forces acting on an entry vehicle versus altitude could be compiled from the various BET sources. These data could then be compared to pre-flight estimates obtained from either wind tunnel tests, model data, etc. Finally, recommended limits on the deviation of these lift and drag forces from a nominal ballistic trajectory could be established and, if so desired, implemented in the BET fitting process. It is noted that these types of analyses have been performed successfully in the past by FM&C analysts in support of the National Aeronautics and Space Administration (NASA) Space Shuttle Program.

FM&C is also proposing the implementation of its own BET generation methodology in support of a limited set of future RV flight tests. Since this methodology utilizes *in situ* dynamic data for vehicle state propagation, it necessarily requires a fully instrumented flight test vehicle. Again, it should be noted that this trajectory determination process would be *atmosphere independent*. This additional post-flight BET data source would be another valuable entry into the previously mentioned database analyses. A companion task to this recommendation is a joint FM&C-USASDC Space Shuttle entry trajectory reconstruction activity. Here, tracking sensors typically utilized during a KMR entry vehicle test, in conjunction with stations that normally support a Shuttle entry, would be used to provide additional tracking coverage. These data would then provide an opportunity to assess the integrity of the various launch, mid-range, and down-range sensors, and, conceivably, could be used to investigate trajectory discrepancies during gaps in tracking coverage between KMR sensors.

The following sections in this report present further discussions on the recommended approaches to implement the concepts described above and a summary of important results and conclusions drawn from the study. Figure 1 provides a basic overview of these various recommendations. Each element of this figure will be described in more detail in later discussions. The majority of the text presented here will address the technical aspects of the proposed recommendations to solve the trajectory fitting discrepancies. In addition, these discussions will include Space Shuttle data from a historical perspective to show the feasibility of the proposed concepts, and provide a basis for the innovative approaches being recommended here to meet the objective of the study.

STATEMENT OF PRELIMINARY HAZARD LIST (PHL) AND COMPLIANCE WITH ENVIRONMENTAL LAWS

- Upon examination of the results from this SBIR Phase I research effort, it has been determined that no hazards exist to be included in the PHL. This statement is also applicable to the proposed Phase II study.

- The SBIR Phase I study presented herein, in addition to the proposed Phase II effort, complies with all existing Federal, State, and local environmental laws and regulations.

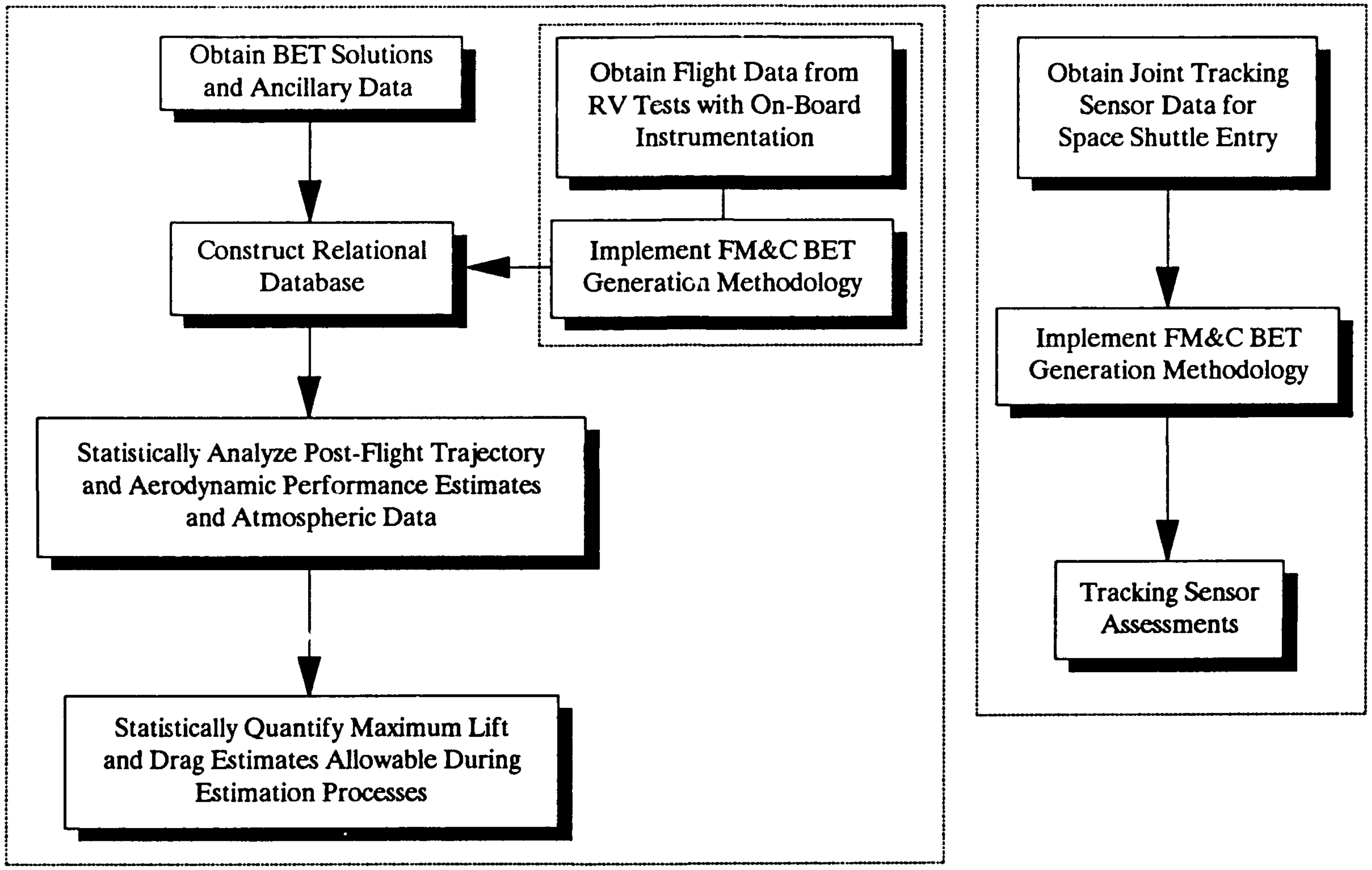

Figure 1. Generic Technical Approach Schematic

III. TECHNICAL APPROACH

This section describes the proposed SBIR Phase II technical effort. There are two (2) subsections presented here to include the development of a post-flight BET database and a discussion of the FM&C BET generation process. The latter is being proposed as an additional source of data for the knowledge base and as the primary contributor for a joint USASDC / FM&C tracking sensor study. Both parts of this proposed effort are intended to be conducted concurrently during the Phase II period of performance. The database discussions will include the types of information that would be incorporated within the database, sample architectures, and several examples of analyses that would be performed. The BET methodology utilized by FM&C analysts will be presented in more detail in the second subsection. Also discussed is a recommended plan for a joint Space Shuttle BET activity to assess KMR tracking sensor performance.

A. DATABASE DEVELOPMENT

This section presents the proposed development of a relational database utilizing BETs (and ancillary data) generated by the USASDC and/or their supporting contractors. The knowledge base will be composed of information from a series of flight tests at KMR to ensure a representative sample of data from which meaningful statistics can be derived. This BET relational database will constitute the principle tool utilized during the Phase II effort. Here, the final analyses will be statistical assessments of various BET parameters to include the critical aerodynamic and atmospheric issues associated with this task. The main objective of the study, as outlined in the program solicitation, will be a statistical quantification of the maximum lift and drag forces on reentry test vehicles as a function of altitude. These results will provide a more realistic assessment of these forces, and other parameters, such that allowable limits can be established and implemented within the various trajectory fitting processes.

Figure 2 presents a general schematic of the proposed database architecture. The following sections will discuss the various data sources to be included in the database, how these data will be assembled within the database structure, and, finally, several examples of the analyses the knowledge base will allow BET analysts to perform. Again, results generated by FM&C analysts from previous NASA Space Shuttle activities will be presented to show the feasibility of these proposed concepts.

A.1. Data Acquisition

Various sources of data are intended to be incorporated within the BET relational database (see Figure 2). The actual BET products generated by the USASDC and/or supporting contractors will constitute the main data source. Again, an

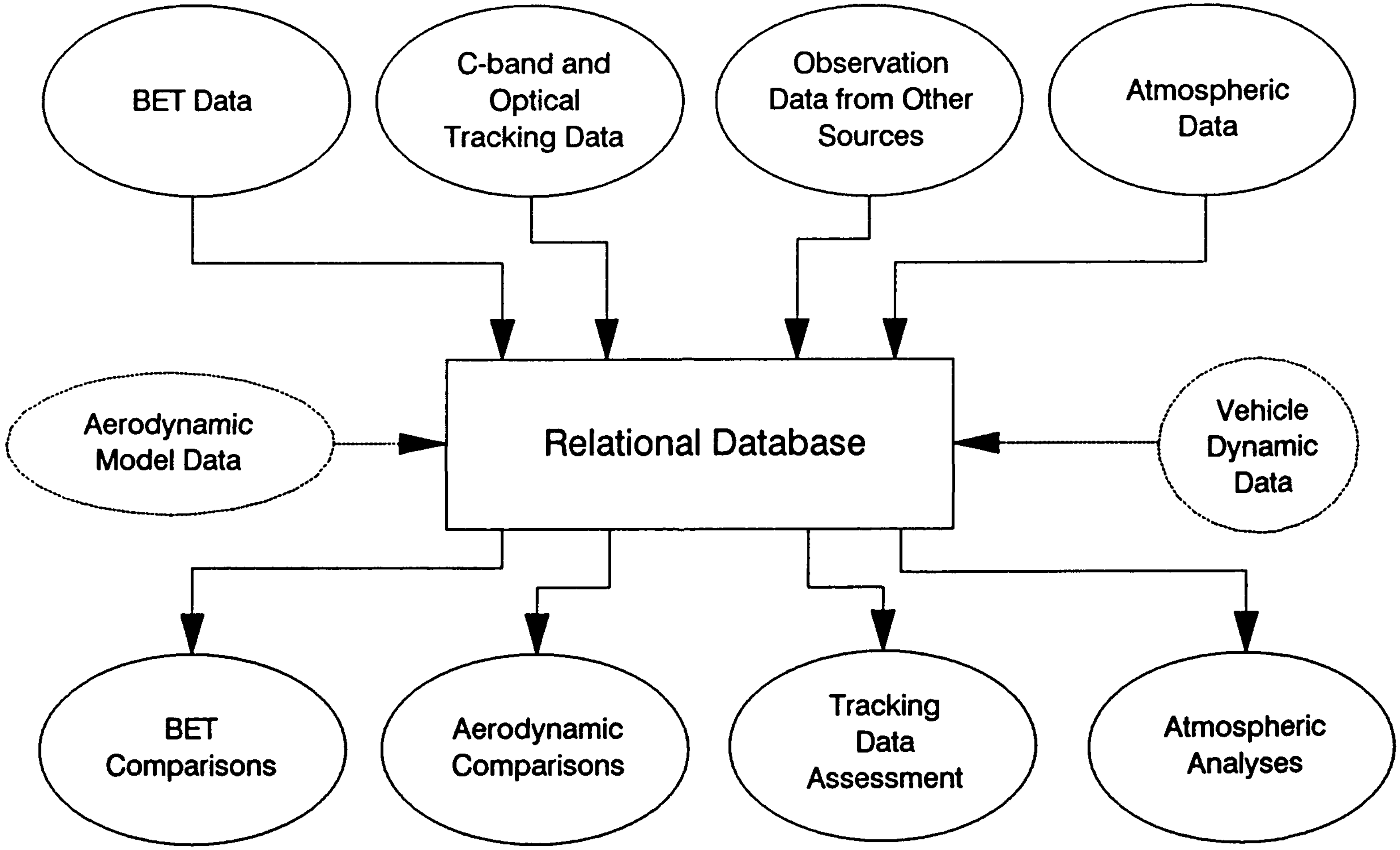

Figure 2. Database Analyses Schematic

ensemble of BETs from numerous (amount to be determined (TBD)) RV test flights, to include archived historical data, will be amassed to ensure the broadest possible database. FM&C analysts will require government-furnished equipment (GFE) that includes access to secure computing facilities of a nature consistent with the security classification of the data and subsequent analyses. This GFE requirement also necessitates a database management system (to be detailed in later sections) commensurate with these computing facilities, and a method of data transferal consistent with same. As a result, the accumulation of the required BET data as mentioned above may be accomplished via magnetic tape or electronic data transferal, depending upon specific security requirements and hardware capabilities.

Additional data required for the proposed relational database are the supporting tracking observations utilized for trajectory reconstruction. These data will include tracking measurements from various sensor complexes in the launch, mid-range, and terminal areas of the vehicle(s) trajectory. Here, these observations will encompass C-band radar data, data from ballistic and RADOT / Super RADOT cameras, and, as indicated in Figure 2, data from other tracking sources (i.e., surveyed impact locations). The usage of these data in the database analyses will be presented in later discussions.

Atmospheric data will also be accumulated within the knowledge base to enhance future studies. These data, as determined on the day of the flight test, will include atmospheric profiles derived from remote measurements (i.e., sounding rockets, balloons, etc.). Also included here is access to the Kwajalein Standard Atmosphere (KSA) and other models of the KMR environment (i.e., Blood-Kwan Atmosphere). This requirement becomes critical, as will be presented in the next section, since the KSA will be used to normalize the air-relative parameters from the alternate BET sources.

Other ancillary data to be included in the BET relational database consists of both aerodynamic model and vehicle dynamic data. The former will be composed of either wind tunnel and/or computational fluid dynamics (CFD) simulated data for further RV aerodynamic performance comparisons. These data will also include mass properties (i.e., weight, moments of inertia, etc.) for the flight test vehicles of interest. Vehicle dynamic data will only be available for flight tests where telemetry data are downlinked from an instrumented RV. These data (accelerometer and rate gyro) are typically generated in a strapped-down configuration to give equivalent body-axes measurements. As with the aforementioned BET data, the tracking observations and atmospheric, aerodynamic model, and vehicle dynamic data are required to be delivered via a data transferal method consistent with the GFE computing facilities.

A.2. Database Architecture

The proposed relational database will be developed to facilitate various statistical analyses of a number of BET-related issues. An example may be the statistical quantification of maximum RV lift and drag profiles as a function of altitude during entry. Again, readers are referred back to Figure 2 for a general overview of the BET database architecture. The section presented here will describe a representative database management system and the information (and architecture) to be included therein.

FM&C analysts will employ a database management system consistent with the computing facilities supplied by the USASDC. It is recommended that a database manager similar to the Boeing Computer Services Relational Information Manager (BCS RIM), Reference 2, be implemented to expedite the proposed analyses. This recommendation is based upon familiarity of the BCS RIM system and its simplicity of use, the projected data volume for this task, and ease of exportability, if so desired, among U.S. government computing systems. Further discussions in this section will assume that readers have some familiarity with database systems, and that the BCS RIM (or similar database manager) is available at USASDC computing facilities.

Historically, FM&C analysts have participated in the development of several databases derived from flight data extracted from numerous NASA Space Shuttle missions (References 3-7). The Langley Research Center (LaRC) Shuttle Archival Flight Database (STSDB), described in Reference 3, was developed to preserve Shuttle entry BET data for use in future aerospace vehicle design activities. FM&C has also developed a series of three (3) Shuttle-derived atmospheric databases (References 4, 5, and 6) for use in both vehicle design analyses and atmospheric model development. The BCS RIM database system was adopted for these activities to enhance exportability since it is widely used throughout the NASA community. Again, selecting data, sorting, and other convenient handling is accommodated in the BCS RIM system with an assortment of relatively simple syntax. More importantly, associated personal computer (PC) software is commercially available that allows extensive analyses within the office workspace environment.

FM&C analysts have also developed a pair of relational databases containing solutions for a series of longitudinal and lateral/directional maneuvers during the entry phases of the first sixteen (16) Space Shuttle missions (Reference 7). These databases contain results from a major flight test activity that evaluated Shuttle Orbiter reaction control system (RCS) and aerodynamic control surface effectiveness. Also included here was an assessment of the post-flight stability derivative determinations. These archival databases were utilized to verify Shuttle Orbiter performance predictions and, as a result of the study, the entry flight envelope for the Orbiter was expanded. Various data sources were utilized for the databases to include solutions from the Rockwell Corporation, the NASA Johnson Space Center (JSC), Dryden Flight Research Center (DFRC), and the Air Force Flight Test Center (AFFTC). Predicted quantities from the final Shuttle Orbiter Aerodynamic Design Data Book (ADDB) were also incorporated.

The brief database discussions presented above are offered to illustrate the feasibility of developing a relational database(s) composed of BET solutions for multiple RV flight tests at the KMR. It also serves as an introduction to the methodology that is proposed herein. This database methodology will be expanded upon in the text to follow, as well as describe the proposed *schema* to enable use of same. Preliminary database schema have been defined such that analysts will be able to compare BET results for a particular RV flight, a specific BET source, specified season, RV class, etc. These preliminary schema are based upon current knowledge of the available data and on expected needs for future analyses. Of course, the number of parameters (*attributes*) in each *relation* in the database will depend upon the amount of various post-flight data (i.e., BET sources) available.

The proposed database, **KMRBET**, is composed of five (5) relations: **GENDAT**, **PREAERO**, **BETDAT**, **RESDAT**, and **ATMDAT** as shown in Figure 3. The relation **GENDAT** includes flight test data common to all BET sources. Relation **PREAERO** contains pre-flight predictions of vehicle aerodynamic coefficients (i.e., via wind tunnel data, model data, etc.) common to each class of RV. Table 1 shows the adopted attributes of the data to be loaded into these two relations. Included here are the parameter name, type, a brief description, and units (if applicable). Shown thereon, for relation **GENDAT**, are the alphanumeric identifiers RVCLS and FLT describing the vehicle class and flight test, respectively, and an integer (FLTNUM) to signify a unique flight number. Note that the attribute FLTNUM will allow selection across the various relations in order to correlate data. Also, an indicator of the total number of BET sources for this flight test is provided by the parameter NBETS. The integer parameters MONTH, DAY, and YEAR are utilized to indicate the flight test date. The time of launch is signified by the attribute TOL in Greenwich Mean Time (GMT) seconds on the day of launch. The aerodynamic reference area for the reentry vehicle is loaded via the parameter SREF. Finally, an assortment of vehicle mass properties data are adopted through the attributes MASS (vehicle mass), XCG, YCG, and ZCG (c.g. locations), and IXX, IYY, and IZZ (moments of inertia). Again, readers should note that the attributes in relation **GENDAT** are common to all BETs for the specific flight test number, and that a row will exist in this relation for each flight.

The relation **PREAERO** consists of nine (9) attributes. Parameter RVCLS is the same as presented above in relation **GENDAT**. The attributes MACH and ALPHA

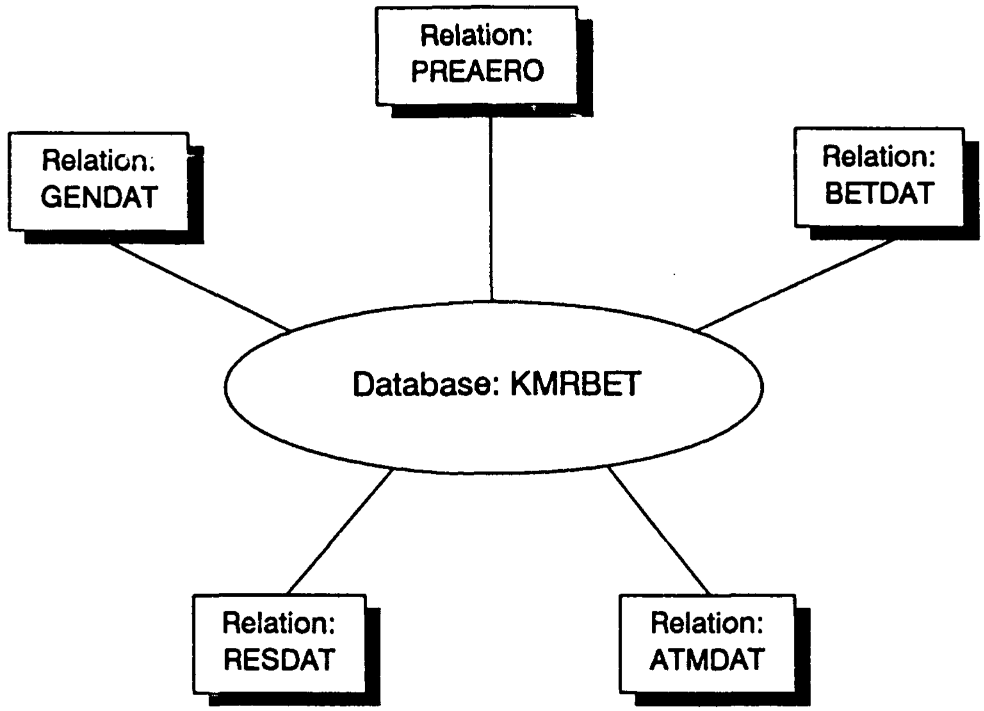

Figure 3. Database: KMRBET Schematic

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are the pre-flight test condition Mach number and angle-of-attack, respectively, to allow appropriate comparisons between predicted and estimated aerodynamic coefficients. As described in Table 1, CL-P, CD-P, and CS-P are the pre-flight predicted aerodynamic coefficients of lift, drag, and side force, respectively. Also included here is the predicted lift-to-drag (L/D) ratio, LOD-P. The moment coefficients (roll, pitch, and yaw) are loaded into relation **PREAERO** via the attributes CLR-P, CMP-P, and CNY-P. Readers should recognize here that the predicted aerodynamic coefficients are assumed to be common throughout a specific vehicle *class* and, hence, can be correlated with associated estimated values via the alphanumeric identifier RVCLS.

The associated BET data for each flight test will be loaded into relation **BETDAT.** Table 2 presents a preliminary list if 34 attributes to be included in this relation. Although the table is self-explanatory, several parameters will be discussed here in more detail. Again, the attribute FLTNUM is the unique flight test number that

RELATION	ATTRIBUTE	TYPE	DEFINITION	UNITS
GENDAT	RVCLS	Text, 12	Alphanumeric identifier specifying vehicle class	N/A
	FLT	Text, 12	Unique alphanumeric identifier for flight test	
	FLTNUM	Integer	Unique flight number for test	
	NBETS	Integer	Number of BET sources for this flight test	
	YEAR	Integer	Year of flight test	
	MONTH	Integer	Month of flight test	
	DAY	Integer	Day of flight test	
	TOL	Real	Time of launch	GMT sec
	SREF	Real	Aerodynamic reference area	m**2
	MASS	Real	Vehicle mass	kg
	XCG	Real	X-component of c.g. in body-axes coordinates	m
	YCG	Real	Y-component of c.g. in body-axes coordinates	m
	ZCG	Real	Z-component of c.g. in body-axes coordinates	m
	IXX	Real	Moment of inertia about X-body axis	kg-m**2
	IYY	Real	Moment of inertia about Y-body axis	kg-m**2
	IZZ	Real	Moment of inertia about Z-body axis	kg-m**2
PREAERO	RVCLS	Text, 12	Alphanumeric identifier specifying vehicle class	N/A
	MACH	Real	Mach number	N/A
	ALPHA	Real	Angle-of-attack	deg
	CL-P	Real	Predicted lift coefficient (see note)	N/A
	CD-P	Real	Predicted drag coefficient	
	CS-P	Real	Predicted side force coefficient	
	LOD-P	Real	Predicted lift-to-drag ratio	
	CLR-P	Real	Predicted rolling moment coefficient	
	CMP-P	Real	Predicted pitching moment coefficient	
	CNY-P	Real	Predicted yawing moment coefficient	

Note: Predicted aerodynamic design data based on KSA and SREF

Table 1. Database schema, Relations: **GENDAT** and **PREAERO**

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permits cross-correlation between relations. The integers BETNUM and DYDAT are flags to indicate the BET source number and usage of on-board dynamic data for trajectory reconstruction, respectively. The former will be utilized to distinguish between the various KMR BET analysts and, for future analyses, an appropriate numbering system will have to be developed. Attribute DTLAUNCH is the corresponding trajectory time referenced to the time of launch (TOL in relation **GENDAT**) in seconds. It is currently being proposed to include BET data in relation **BETDAT** at a nominal rate of 1 Hz. Continuing, the vehicle position, velocity, and attitude are shown next. Readers should note that the flight path parameters shown here are referenced to a geodetic Earth and planet-relative velocity vector. This convention will permit more meaningful comparisons by rendering each BET source as independent from any specific source of atmospheric data. Of course, additional

RELATION	ATTRIBUTE	TYPE	DEFINITION	UNITS
BETDAT	FLTNUM	Integer	Flight number for this test	N/A
	BETNUM	Integer	BET source number	
	DYDAT	Integer	On-board dynamic data flag (0 - *not available*, 1 - *available*)	
	DTLAUNCH	Real	Time from launch	sec
	VEL	Real	Planet-relative velocity at time DTLAUNCH	m/sec
	GAM	Real	Planet-relative flight path angle	deg
	AZ	Real	Planet-relative heading	deg
	ALT	Real	Altitude above the Fischer ellipsoid	m
	GLAT	Real	Geodetic latitude	deg
	LON	Real	East longitude	deg
	SIGMA	Real	Roll angle about planet-relative velocity vector	deg
	BETA	Real	Planet-relative sideslip angle	deg
	ALPHA	Real	Planet-relative angle-of-attack	deg
	ROLL	Real	Euler roll angle	deg
	PITCH	Real	Euler pitch angle	deg
	YAW	Real	Euler yaw angle	deg
	MACHB	Real	Mach number based VEL (relative to KSA)	N/A
	QBAR	Real	Dynamic pressure based VEL (relative to KSA)	N/m**2
	PB	Real	Roll rate about body X-axis	deg/s
	QB	Real	Pitch rate about body Y-axis	deg/s
	RB	Real	Yaw rate about body Z-axis	deg/s
	AXB	*Real*	*Acceleration along body X-axis*	m/s**2
	AYB	Real	Acceleration along body Y-axis	m/s**2
	AZB	Real	Acceleration along body Z-axis	m/s**2
	PDOTB	Real	Angular acceleration about body X-axis	deg/s**2
	QDOTB	Real	Angular acceleration about body Y-axis	deg/s**2
	RDOTB	Real	Angular acceleration about body Z-axis	deg/s**2
	CL-F	Real	Flight-estimated aerodynamic lift coefficient (see note)	N/A
	CD-F	Real	Estimated drag coefficient	
	CS-F	Real	Estimated side force coefficient	
	LOD-F	Real	Estimated lift-to-drag ratio	
	CLR-F	Real	Estimated rolling moment coefficient	
	CMP-F	Real	Estimated pitching moment coefficient	
	CNY-F	Real	Estimated yawing moment coefficient	

Note: Flight-estimated aerodynamics are based on KSA and SREF

Table 2. Database schema, Relation **BETDAT**

atmospheric analyses will be presented in a later discussion as mentioned earlier. Moreover, it is noted that the vehicle state parameters shown here could also include position and velocity components referenced to a cartesian coordinate system if so desired.

The flight Mach number (MACHB) and dynamic pressure (QBAR) are included next in relation **BETDAT**. These parameters are based on the previously mentioned planet-relative velocity and are normalized to the KSA as follows:

$$M_R = V_R / c_s$$

and

$$q_R = \frac{1}{2} \rho V_R^2$$

where V_R is the planet-relative velocity, c_s is the speed of sound, and ρ is the density based on the KSA. The speed of sound is computed by:

$$c_s = (\gamma R^* T)^{1/2}$$

where γ is the ratio of specific heats, R^* is the universal gas constant, and T is the KSA temperature. Readers should note that the Mach number shown here will provide the "Mach slice" from which flight-estimated and pre-flight aerodynamic coefficients can be compared. Next, vehicle body-axes dynamics are incorporated within **BETDAT** to include angular rates, linear accelerations, and angular accelerations. If on-board instrumentation were available for the test flight (indicated via attribute DYDAT), then these data are equivalent body-axes measurements utilized in the BET generation process. Finally, the flight-estimated aerodynamic coefficients (to include lift-to-drag ratio) are listed. Note that these attributes are typically treated as part of the vehicle state vector within the trajectory estimation scheme.

The next requirement for the **KMRBET** database will be the acquisition of supporting tracking observations as discussed earlier. Although the actual tracking measurements for each RV flight test will not be directly included in the relational database, they will be implemented during its development. Here, *computed* observations will be formulated from the trajectory data provided in relation **BETDAT** for the flight test of interest. Thus, observation residuals (observed value -

computed value) can be be computed from the given tracking measurements. Both the computed observations and residual computations will be performed via software (program PREDICT) developed and currently used by FM&C analysts. These observation residuals will be loaded into the database through the relation **RESDAT**. A preliminary (sample) list of **RESDAT** attributes and their definitions are shown below in Table 3.

As in the previous relations, the flight number, BET source number, and time from launch are given by the parameters FLTNUM, BETNUM, and DTLAUNCH, respectively. The attributes that follow are a sample of various observation residuals from C- and P-band radars and cameras in the terminal region at Kwajalein. Included here are range, azimuth, and elevation residuals for several radar sensors, and azimuth and elevation residuals generated from camera measurements. It should be noted that an attribute would be included in **RESDAT** for each type of

RELATION	ATTRIBUTE	TYPE	DEFINITION	UNITS
RESDAT	FLTNUM	Integer	Flight number for this test	N/A
	BETNUM	Integer	BET source number	N/A
	DTLAUNCH	Real	Time from launch	sec
	KMTC-RG	Real	Range residual for FPQ-19 C-band radar (KMTC) at Kwajalein	m
	KMTC-AZ	Real	Azimuth residual (KMTC)	deg
	KMTC-EL	Real	Elevation residual (KMTC)	deg
	KMRC-RG	Real	Range residual for ALCOR C-band radar (KMRC) at Kwajalein	m
	KMRC-AZ	Real	Azimuth residual (KMRC)	deg
	KMRC-EL	Real	Elevation residual (KMRC)	deg
	KMAC-RG	Real	Range residual for ALTAIR P-band radar (KMAC) at Kwajalein	m
	KMAC-AZ	Real	Azimuth residual (KMAC)	deg
	KMAC-EL	Real	Elevation residual (KMAC)	deg
	SR1A-AZ	Real	Azimuth residual for Super Radot (SR1A) at Kwajalein	deg
	SR1A-EL	Real	Elevation residual (SR1A)	deg
	SR3B-AZ	Real	Azimuth residual for Super Radot (SR3B) at Legan	deg
	SR3B-EL	Real	Elevation residual (SR3B)	deg
	SR6A-AZ	Real	Azimuth residual for Super Radot (SR6A) at Gagan	deg
	SR6A-EL	Real	Elevation residual (SR6A)	deg
	R1A-AZ	Real	Azimuth residual for Radot (R1A) at Kwajalein	deg
	R1A-EL	Real	Elevation residual (R1A)	deg

Table 3. Database schema, Relation: **RESDAT**

measurement provided by a tracking sensor along the vehicle flight path. Hence, more parameters than are indicated in Table 3 would be available for further analyses. Additionally, though not shown in Table 3, tracking sensors in the launch and mid-range (i.e., Kaena Point, Hawaii) areas could be included to assess sensor performance in these regions.

Atmospheric data will also be included in the relational database **KMRBET**. Here, the Kwajalein Standard Atmosphere (KSA) is the proposed reference to which other atmospheric parameters will be normalized. If available, measured atmospheric data (derived via remote sensing measurements) will be included in the relation **ATMDAT** (see Table 4). For BET sources implementing other atmospheric model data (i.e., the Blood-Kwan Atmosphere), the associated atmospheric parameters will replace the measured quantities. Obviously, if the KSA was utilized for the BET, an entry into **ATMDAT** would not be made. It is also proposed that flight-derived atmospheric parameters be included in this relation to facilitate additional analyses.

Shown in Table 4 are the previously defined attributes MONTH, YEAR, FLTNUM, and BETNUM to be used as identifiers and sorting mechanisms. The attributes MODEL and DMOD are implemented as a flag and narrative descriptor, respectively, if atmospheric model data (other than the KSA) were used in the BET process. Included next are the KSA position variables of altitude, geodetic latitude, and longitude, and corresponding values of KSA density (DKSA), temperature (TKSA), and pressure (PKSA). The associated measured (or modeled) and flight-derived atmospheric quantities are also described in Table 4. Readers should note that the density and pressure data are presented as ratios normalized to the KSA.

The flight-derived parameters are computed from available BET data (i.e., Relation: **BETDAT**) and knowledge of the predicted pre-flight aerodynamic coefficients (Relation: **PREAERO**). These techniques have been employed extensively in the past by FM&C analysts in support of post-flight Space Shuttle BET activities. Results of same will be presented in more detail in the next section on database utilization. For the sake of completeness, though, this methodology will be summarized briefly here. The flight-derived density (ρ_{C_N}) is based on pre-flight estimates of the normal force coefficient as follows:

$$\rho_{C_N} = (2\,m / S_{ref})\,[\,A_N / (V_A^{\,2}\, C_{Np})\,]$$

where m is the spacecraft mass, S_{ref} is the aerodynamic reference area, A_N is the normal acceleration, V_A is the air-relative velocity, and C_{Np} is the predicted normal

RELATION	ATTRIBUTE	TYPE	DEFINITION	UNITS
	MONTH	Integer	Month of flight test	
	YEAR	Integer	Year of flight test	
	FLTNUM	Integer	Flight number	
	BETNUM	Integer	BET source number	N/A
	MODEL	Integer	Flag to indicate atmospheric model data: 0 - no (i.e., measured data), 1 - yes	
	DMOD	Text, 12	Alphanumeric model descriptor if MODEL = 1	
	ALT	Real	Altitude above Fischer ellipsoid	m
	GLAT	Real	Geodetic latitude	deg
	LON	Real	Longitude	deg
	DKSA	Real	Kwajalein Standard Atmosphere (KSA) density	kg/m**3
	DMES/DK	Real	Density ratio, measured (or modeled) to KSA density	N/A
	DDER/DK	Real	Density ratio, flight-derived to KSA density	
ATMDAT	TKSA	Real	KSA temperature	^{o}K
	TMES	Real	Measured (or modeled) temperature	^{o}K
	TDER	Real	Flight-derived temperature	^{o}K
	PKSA	Real	KSA pressure	N/m**2
	PMES/PK	Real	Pressure ratio, measured (or modeled) to KSA pressure	N/A
	PDER/PK	Real	Pressure ratio, flight-derived to KSA pressure	
	U-WKSA	Real	North to South wind component, KSA	
	V-WKSA	Real	East to West wind component, KSA	
	W-WKSA	Real	Vertical wind component, KSA	
	U-WMES	Real	North to South wind component, measured (or modeled)	m/sec
	V-WMES	Real	East to West wind component, measured (or modeled)	
	W-WMES	Real	Vertical wind component, measured (or modeled)	

Table 4. Database schema, Relation: **ATMDAT**

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force coefficient. Additionally, atmospheric pressure (P) and temperature (T) are obtained via integration of the hydrostatic equation in conjunction with the perfect gas law as follows:

$$dP = -\rho_{C_N}\, g\, dh$$

and

$$P = [R^{*}\, T\, \rho_{C_N}] / \mu$$

where g is the gravitational acceleration, h is the spacecraft altitude, R^* is the universal gas constant, and μ is the molecular weight.

Finally, as indicated in Table 4, values for the KSA and measured (or modeled) North, East, and vertical components of the winds aloft are included for additional comparisons. Relation **ATMDAT** will allow BET analysts to evaluate dispersions of various measured (or modeled) and derived atmospheric data from the corresponding KSA-modeled predictions. Examples of such analyses will be presented in the next section.

A.3. Database Utilization

This section presents sample results that may be generated by analysts utilizing the relational database **KMRBET**. Examples and figures produced from several of the relations discussed earlier (i.e., **BETDAT**, **RESDAT**, and **ATMDAT**) will be shown. The results presented here were produced from NASA Space Shuttle data compiled by FM&C analysts to serve as a demonstration of the feasibility of this proposed Phase II study. Readers should recognize that the Shuttle results shown here could be applied to a series of KMR flight tests since the two studies are certainly similar.

As discussed in the previous section, the relation **BETDAT** will include various estimates of aerodynamic coefficients from each BET source. These data can be compiled and analyzed to create an equivalent set of ensemble statistics such that dispersions of the aerodynamic performance estimates can be studied. Additionally, comparisons with predicted design data can also be performed. Figure 4 demonstrates this concept by showing a representative Space Shuttle (STS-35 in this case) sample of lift, drag, and L/D comparisons. These longitudinal aerodynamic performance comparisons are presented as a percentage of the flight-derived coefficient versus Mach number. The differences are defined as flight-extracted minus the predicted values. The shaded areas that are superimposed on these plots define statistical bands of the expected aerodynamic comparison accuracy derived from an ensemble of 22 of the first 24 Shuttle entry flights. Readers should also note that the predicted values used here have been rectified utilizing the so-called Flight Assessment Delta (FAD26) incrementals (Reference 8). These corrections were determined from a concensus opinion of various Shuttle project aerodynamicists based on analyses from flights through the STS-26 mission.

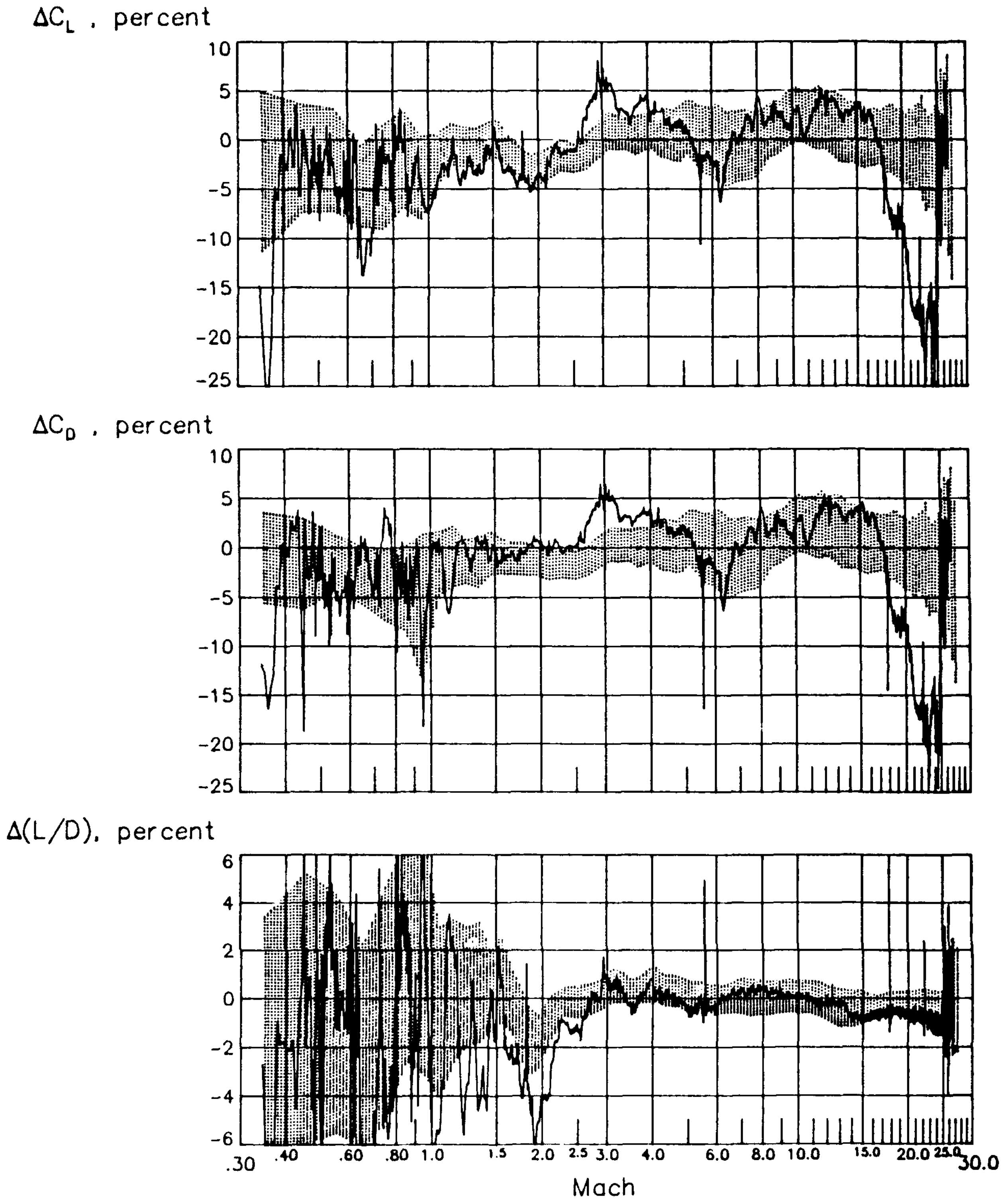

Figure 4. Representative Space Shuttle Lift, Drag, and L/D Comparisons

As indicated by the figure, much of the flight-derived results for the STS-35 entry conform to expected levels of aerodynamic comparison accuracy based on previous missions. It can be observed, though, that a major departure in the lift and drag coefficients occurs above Mach 20. Here, an approximate 20% over-prediction is shown. This result, as will be discussed later, can be attributed to a density ***bulge*** in the measured density profile for the STS-35 entry flight. Thus, this measured density is reflected in the flight-derived estimates of the force coefficients as shown here. The type of analyses demonstrated by Figure 4 can also be applied to a series of RV flight tests at the KMR. As a result, statistical trends can be established whereby estimated dispersions in lift and drag forces can be quantified as functions of either Mach number and/or altitude.

Similar to the BET data above, the relation **RESDAT** can be utilized to assess the performance of various tracking sensors for numerous RV flight tests. Here, tracking observation residuals associated with each BET source can be compiled for further statistical analyses. Observation biases, inaccuracies in the surveyed sensor locations, and timing errors are several examples of the types of anomalies that can be isolated from such investigations. Again, the goals here are statistical trends in the tracking measurement residuals where sensors located at any point along the vehicle flight path (i.e., launch, mid-range, and impact regions) could be included in the investigation.

Figure 5 presents an example of such analyses for a series of Space Shuttle entries. Included here are composite range residuals for five (5) Shuttle missions from the FPQ-19 C-band radar at Kwajalein Island (KMTC). A typical Space Shuttle entry profile would correspond to approximately 120-125 km in altitude during the KMTC tracking period. The range residuals are plotted in meters versus a normalized time defined by the start of KMTC tracking coverage for each Shuttle entry trajectory. Also annotated on this figure are the composite mean (μ) and standard deviation (σ) for these residuals. As indicated by the figure, an apparent 1σ composite range bias ($\approx$12 m) is determined from this analysis. Also shown is an approximate 3σ composite residual "fit" to these range measurements. An interesting note should be made here concerning the considerable signal retained by the STS-11 (41-B) residuals. This Shuttle entry was the first to be supported by a Kwajalein tracking complex. It was postulated, though never confirmed, that a surveyed longitude error of approximately .0005 degrees for the KMTC radar location may have contributed to this final residual pattern. Finally, it is important that readers are aware that C-band coverage for the Shuttle is only provided by skin tracking and does not accommodate beacon tracking that may be more familiar to KMR analysts.

A second example of tracking residual analyses provided by the relation **RESDAT** is shown in Figure 6. Here, composite range residuals from the FPQ-14 C-band radar

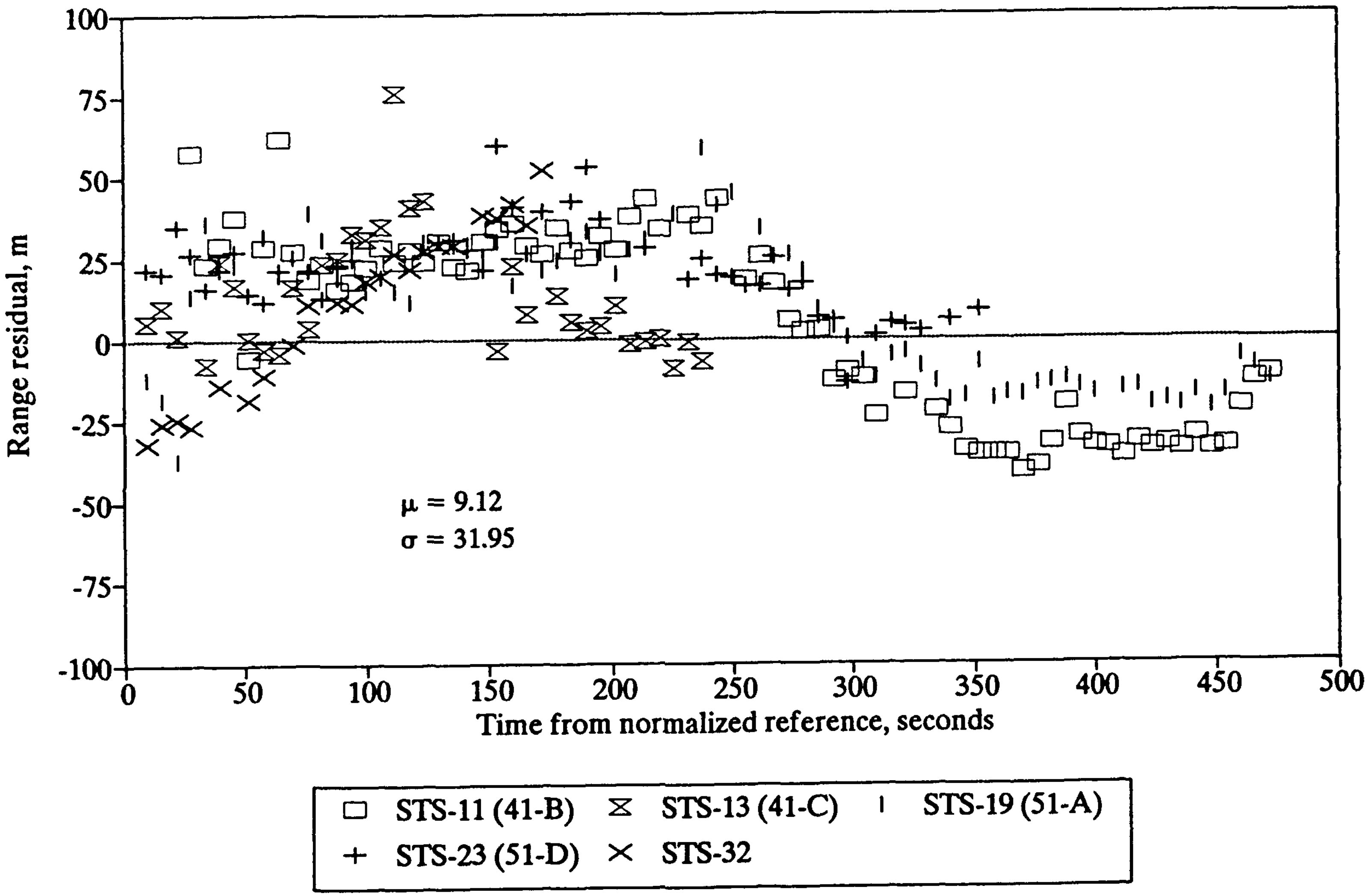

Figure 5. Composite Shuttle Range Residuals for KMTC Tracking Sensor

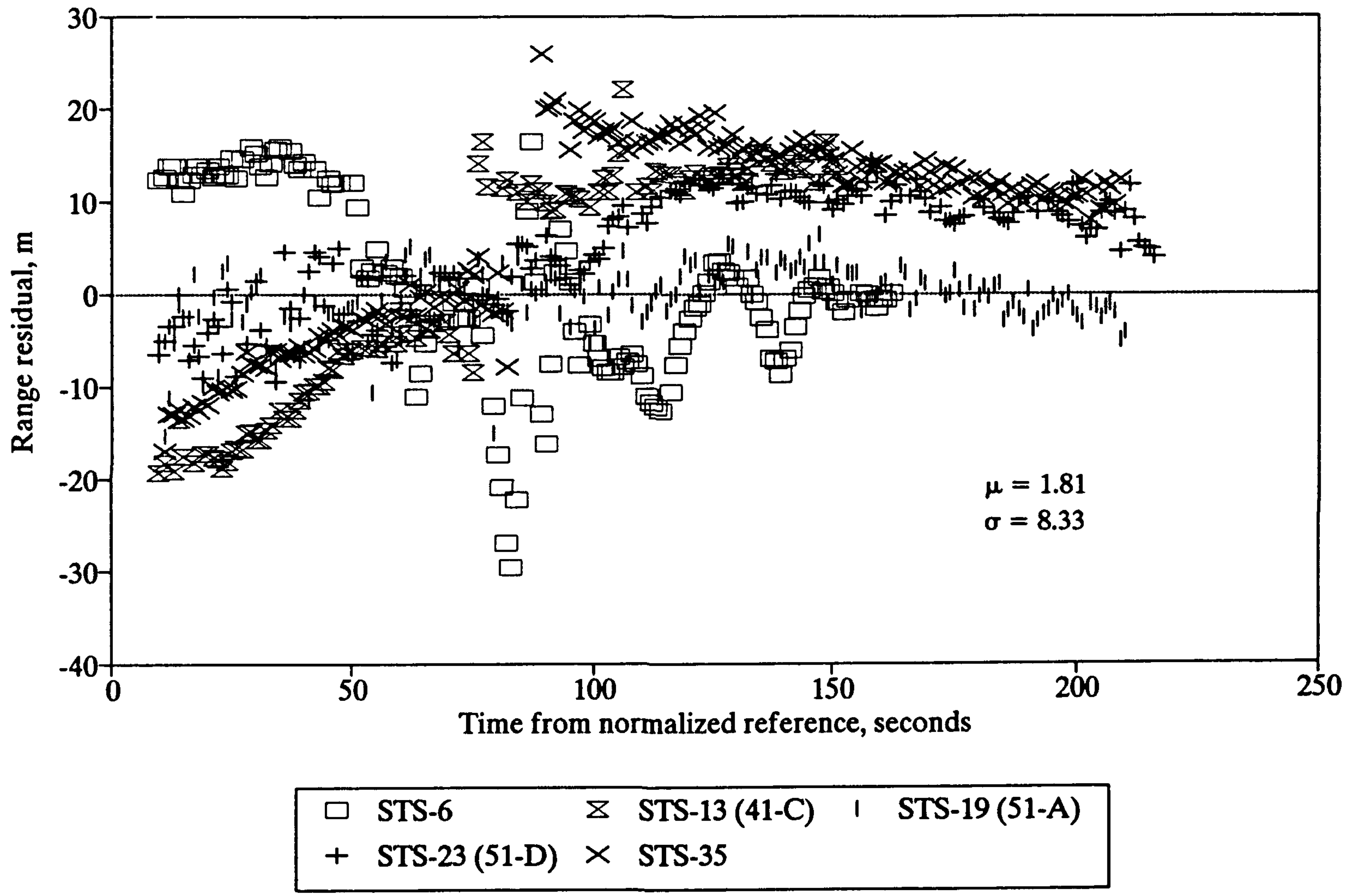

Figure 6. Composite Shuttle Range Residuals for Kaena Point Tracking Sensor

at Kaena Point, Hawaii (KPTC) are shown, again, for a series of five (5) Space Shuttle entry trajectories. A typical altitude profile for the Shuttle during this period of coverage corresponds to approximately 70-75 km, and represents the only mid-range tracking available during entry. This tracking scenario would be similar for entry vehicle tests performed at Kwajalein. As shown in the figure, the composite statistics indicate well-behaved residual patterns of approximately zero (0) mean and 1σ standard deviation. Readers should note, though, that these values do not reflect the 1σ-2σ discontinuities associated with several trajectories (i.e., STS-13 and STS-35) at approximately 80 seconds of normalized time. These anomalies are currently being attributed to shifts in the return signals via skin tracking from one area of the Shuttle vehicle to another. Further investigation, though, is needed to confirm this conclusion.

Finally, the previously discussed database relation **ATMDAT** can be utilized for extensive atmospheric analyses and comparisons. As presented earlier, numerous Space Shuttle atmospheric database evaluations have been performed and published in the last decade by FM&C analysts. A sample of such analyses is shown in Figure 7. Included here are several sets of atmospheric density and temperature profiles plotted versus altitude (45-95 km) for the STS-35 Shuttle entry. The smaller figure at the top presents a corresponding ground track for this mission during the same 45-95 km altitude region. The various sources for density and temperature data as shown in the figure correspond to flight-derived values (DERIVED), profiles usurped from the Marshall Space Flight Center (MSFC) Global Reference Atmospheric Model (GRAM) and the Air Force 1978 Standard Atmospheres (AF'78), and measured data (MEASURED) derived from remote sensing techniques employed by the National Weather Service (NWS). It is noted that the density for each of these atmospheric sources has been normalized to the 1976 Standard Atmosphere. Readers can now see the apparent "density bulge" in the measured profile that was referred to earlier during the aerodynamic comparison discussions. Again, this structure occurs near the altitude region of 70 km, or approximately Mach 20 during the Shuttle entry. Readers should also note the high resolution associated with the Shuttle-derived atmospheric data as shown in Figure 7. This phenomenon can be attributed to the low vertical descent rate (a maximum of approximately 200 m/sec) of the Orbiter during entry. It is noted that past experience has shown Shuttle-derived density profiles to be reasonably smooth and devoid of any major density shears and/or other abrupt structure. Moreover, based on an ensemble of Shuttle flights, the flight-derived atmospheres have agreed favorably with measured atmospheric profiles.

The discussion above is included here to present the idea of a "RV-derived atmosphere" as alluded to earlier by the associated parameters in relation **ATMDAT**. Here, with pre-flight knowledge of vehicle mass properties and predicted aerodynamic coefficients, RV-derived atmospheric density, pressure, and temperature

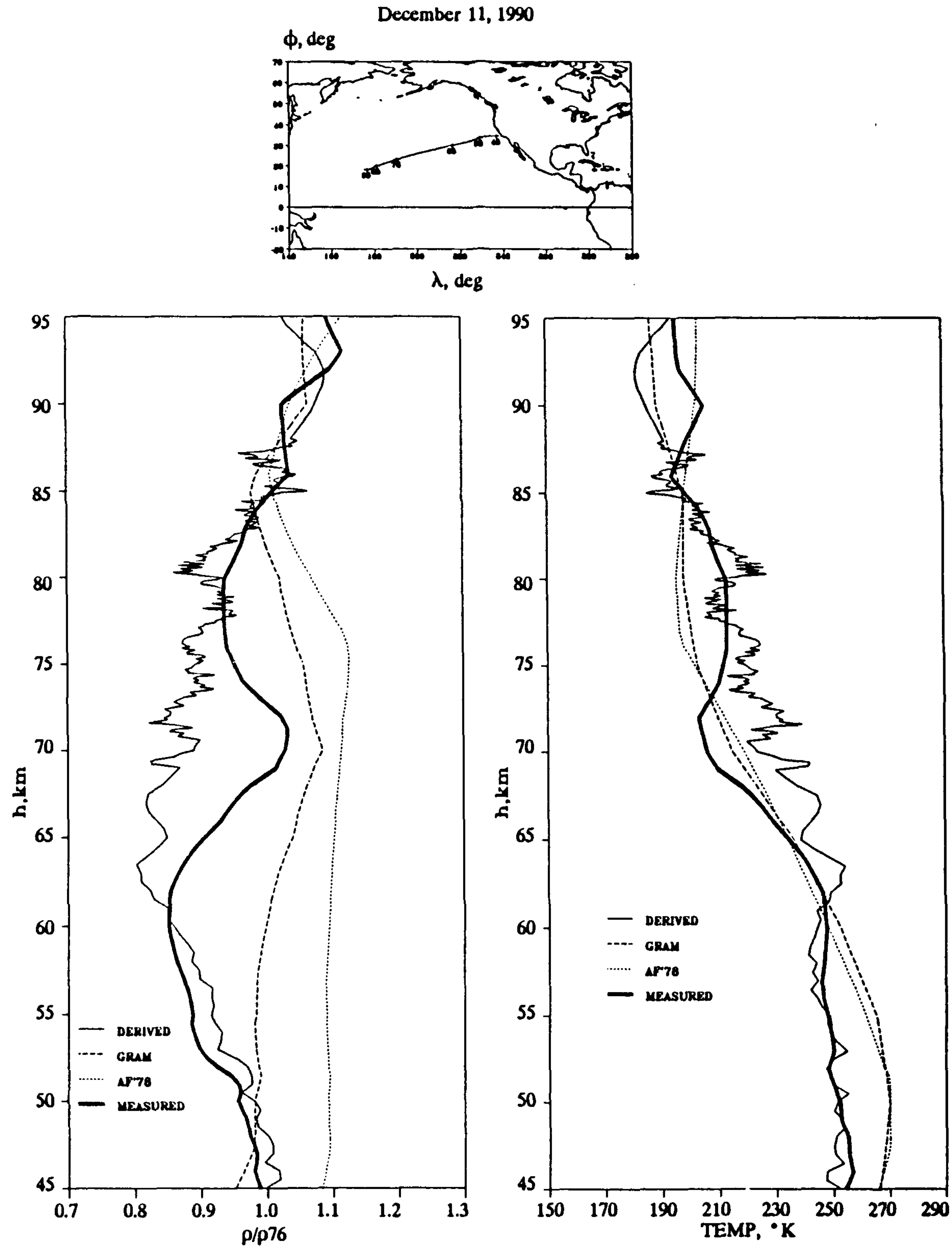

Figure 7. Space Shuttle (STS-35) Density and Temperature Comparisons

can be developed with available BET information as discussed earlier. For KMR tests employing instrumented entry vehicles, the FM&C BET methodology would also be proposed as a source of both trajectory data and flight-derived atmospheric information. The FM&C BET generation process will be discussed in more detail in the next section. Additionally, readers should recognize that the degree of vertical resolution of a RV-derived atmosphere will be substantially decreased when compared to the previous Space Shuttle results. This is attributed to the extremely high descent rate of a KMR entry test vehicle. However, these results would still provide an excellent source of data for comparison with both measured and modeled atmospheric profiles, and could conceivably be implemented in model updates to the KMR environment.

A final example of atmospheric analyses that would be provided by the relation **ATMDAT** is presented in Figure 8. Included here are monthly (or seasonal) comparisons between Shuttle-derived and model (GRAM and AF'78) densities plotted versus altitude. Again, the density sources are normalized to the 1976 Standard Atmosphere and results are shown for the months of April, September, and November. The shaded areas correspond to Shuttle-derived densities compiled from a database of thirty-two (32) entry flights. As indicated by the figure, the flight-derived results show an appreciable shift in density at altitudes above 75 km. However, the results tend to agree more favorably with both the GRAM and AF'78 models during the altitude region of 45-75 km. This type of analysis could be readily applied to the KMR environment as discussed previously. Here, both measured and RV-derived atmospheric parameters would be compiled and compared extensively with data from the KSA and other available models.

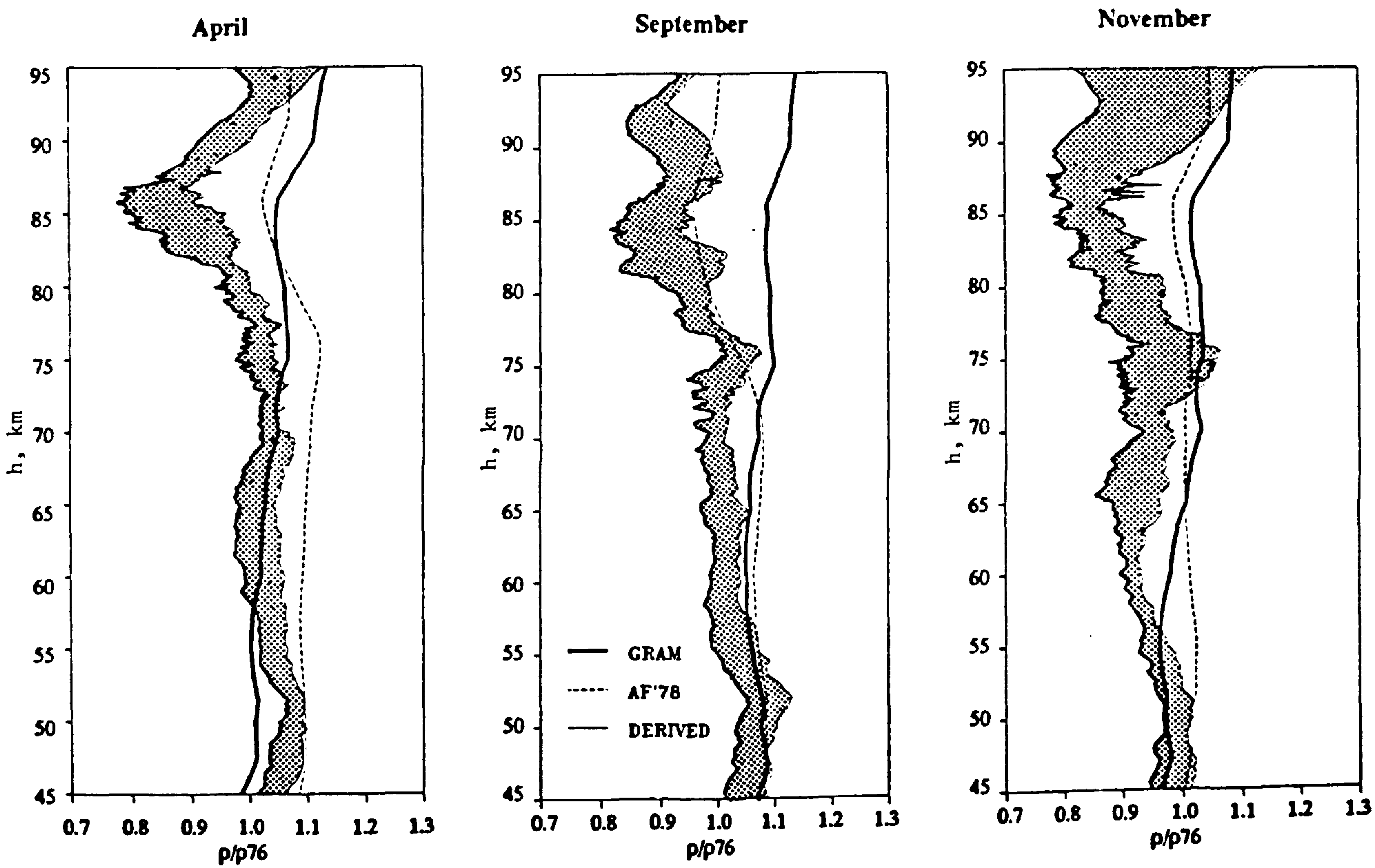

Figure 8. Comparisons Between Monthly Shuttle-derived and Model Densities

B. FM&C BET GENERATION METHODOLOGY / JOINT TRACKING SENSOR STUDY

This section is composed of two (2) subtopics. The first is a brief overview of the post-flight BET generation process employed by FM&C analysts. These techniques, as discussed earlier, have been implemented successfully for numerous NASA Space Shuttle reentry trajectory reconstruction investigations (i.e., Reference 9). Additionally, the FM&C BET methodology is currently being applied to pre-flight analyses for the NASA Aeroassist Flight Experiment (AFE). This work includes several extensive software modifications to be presented in more detail in later discussions.

Each input element to the FM&C BET process will be described briefly. The discussions will culminate with several output products to include the resulting inertial trajectory history for the vehicle, implementation of atmospheric data to generate the final BET, and the application of post-processing utilities for further aerodynamic performance and atmospheric comparisons. The FM&C BET methodology is being proposed here in support of this SBIR project in two (2) areas. First, this methodology can be utilized to provide BET results for a restricted set of entry vehicle tests at the KMR. These tests would include those vehicles with on-board instrumentation as discussed earlier. As a result, this BET would provide yet another source of data to be included in the proposed database analyses (Section A). Additionally, the FM&C BET process will be the primary data source for a proposed Space Shuttle tracking sensor study with other KMR analysts. This is the second subtopic as presented herein.

The joint Space Shuttle tracking sensor exercise is being proposed to provide extensive KMR sensor performance analyses. Here, a number of Department of Defense (DoD) and NASA tracking stations would be activated in the KMR launch, mid-range, and impact regions during a Shuttle descent phase. As a result, sensor bias and surveyed location studies, as well as FM&C-generated Shuttle BET comparisons, could be performed to enchance future KMR entry vehicle tests. Included in this subsection are discussions of a representative Space Shuttle entry ground track, a typical entry altitude profile to include tracking sensor timelines, and, finally, a sample list of DoD sensor complexes that have supported Shuttle entries in the past.

B.1. FM&C BET Methodology

The FM&C BET generation process is summarized by the schematic shown in Figure 9. As indicated, the methodology is based on the primary software tool ENTREE (Entry Trajectory Estimation program) described in detail in Reference 10. This program is actually a derivative of the Statistical Trajectory Estimation

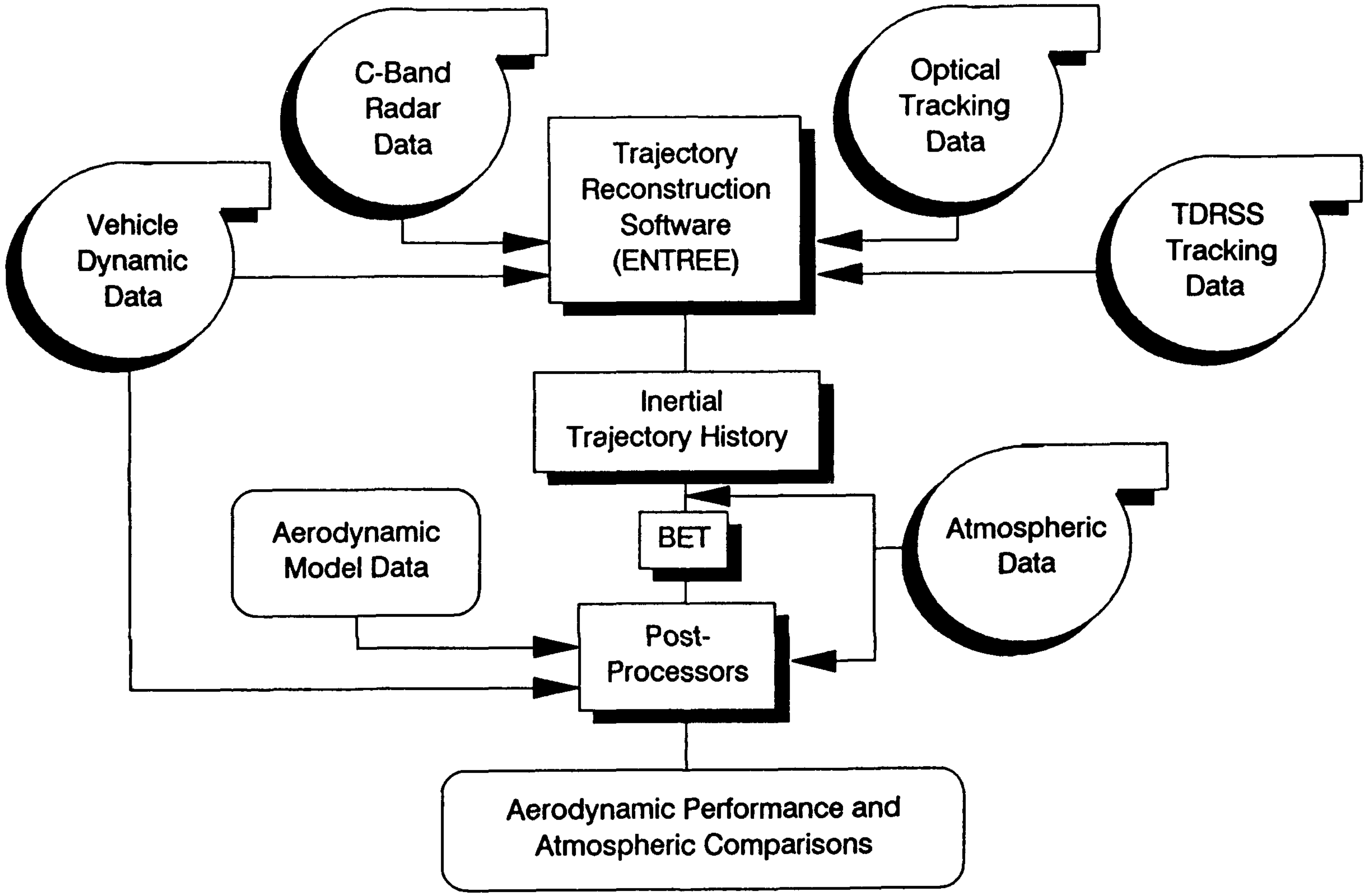

Figure 9. FM&C BET Generation Schematic

Program (STEP) presented in Reference 11. Although still designated as ENTREE, FM&C analysts have made extensive modifications to this code throughout the previously mentioned Space Shuttle (and AFE) trajectory reconstruction activities. These upgrades and modifications have been well documented (see References 12-14) and will only be summarized throughout the ensuing discussions.

The ENTREE program is the integral software utilized to generate the inertial trajectory history of the vehicle. An essential input to the code is a time history of vehicle dynamic data (see Figure 9) to include in situ measurements from on-board linear accelerometers and rate gyros. It is imperative that these data be of inertial quality and configured to report accumulated sensed changes in velocity and attitude information. Additionally, any data quantization associated with these measurements should be nondestructive. By utilizing cubic-spline techniques and various other analytical methods, instantaneous angular rates and linear accelerations are then derived from these data. Moreover, gaps occuring in the telemetry can be filled using these same cubic-spline techniques. These procedures are commonly used by FM&C analysts for Space Shuttle applications. The derived rates and accelerations are then implemented in the equations of motion as replacements for the usual aerodynamic force and moment modeling that may be more familiar to some readers. It should be noted that mathematical formulations for these forces are quite complex and extremely difficult to model for atmospheric reentry vehicles. Thus, by integrating the sensed accelerations and angular rates via the equations of motion, the vehicle aerodynamic models are not needed and the FM&C BET process is rendered "atmospheric independent". As a consequence, a more accurate trajectory estimate is generated. Finally, it should also be noted that these data are referenced to the vehicle body-axes in ENTREE as would be derived from instrumentation in a strapped-down configuration.

A fourth-order Runge Kutta integration scheme is utilized to integrate the equations of motion of the vehicle in ENTREE. Here, the translation equations are integrated using the input accelerometer data, and, likewise, the rotational equations integrated utilizing the angular rate data. This unique integration method uses these gyro and accelerometer measurements as a way to define both external aerodynamic forces and moments acting on the vehicle during reentry. This technique provides for a more precise integrated trajectory as opposed to the mathematical modeling of these forces as discussed above. Hence, by specifying an approximate initial vehicle state, the coupled equations of motion are integrated to yield an entry trajectory in terms of position, velocity, and attitude.

A statistical estimation scheme is employed next in ENTREE by utilizing all the external tracking data (again, Figure 9). These data consist of C-band radar measurements of vehicle range, azimuth, and elevation, optical tracking data (i.e., cinetheodolite camera data utilized for Shuttle entries) that provide measurements of azimuth and elevation angles, and, finally, a unique implementation of Tracking and Data Relay Satellite System (TDRSS) observations. The latter are composed of either S- or K-band range and/or Doppler observations via an array of several geosynchronous relay satellites. FM&C analysts have developed a rather unique capability to process these data in the BET generation scheme (Reference 15). It is noted that these techniques are currently employed for ongoing Space Shuttle activites and will be implemented for post-flight trajectory reconstruction in support of the AFE project. The estimation procedure is initiated by utilizing a regression method to iterate on the initial vehicle state such that a trajectory is generated which statistically satisfies all the input tracking data. After determining the best possible set of initial conditions, the final inertial trajectory history is generated via the previously mentioned state propagation.

The estimation method utilized in the ENTREE software is a weighted least-squares batch filter. This batch estimation procedure uses a weighted least-squares algorithm to collect all the observation statistics, process them in a batch mode, then determine the state correction vector at the epoch time. The covariance of the estimated state is also computed during the integrated vehicle trajectory. Readers should note that the vehicle state vector is typically described by position, velocity, and attitude parameters, but can also (if desired) include up to twenty (20) additional variables to be estimated along with these. For example, a dynamic data error model is provided in ENTREE whereby scale factors, misalignments, and biases are applied to the input acceleration and angular rate measurements and treated as part of the state vector. These variables can be utilized to account for expected inaccuracies inherent to on-board instrumentation. Additionally, measurement biases for each tracking observation type can also be estimated. Finally, it should be stated that up to ten (10) additional variables can be specified as "consider" parameters where they are treated as statistically uncertain with some mean value and standard deviation. These variables are not solved for as part of the state.

The next element in the FM&C BET methodology is the inclusion of atmospheric data. Here, measured and/or modeled data can be employed but, typically, both are used to facilitate further atmospheric comparisons. These data are utilized in conjunction with the previously described inertial trajectory history to generate the final BET. Included here are both planet- and air-relative vehicle state parameters, flight-derived atmospheric parameters (i.e., Mach number, dynamic pressure, density, etc.), flight-derived aerodynamic coefficients, and numerous other variables. This element essentially completes the BET generation process, although an additional function is shown, again, in Figure 9.

This final element consists of various post-processing utilities developed by FM&C analysts to provide for extensive aerodynamic performance and atmospheric comparisons. Sources of input for these utilities include the post-flight BET, vehicle dynamic data, pre-flight estimates of aerodynamic coefficients, and, of course, the atmospheric data mentioned above. For more aerodynamically complicated vehicles (i.e., Shuttle), knowledge of RCS effects, control surface deflections, and heat shield ablation effects would have to be obtained for rigorous post-flight aerodynamic comparisons. Hence, for FM&C support of complex KMR reentry vehicles, these same data would have to be available. Examples of analyses from this final element have been presented earlier in the database development discussions. Although the results that have been shown are for Space Shuttle applications, it should be noted again that similarities certainly exist with entry vehicle tests at the KMR. It is proposed that the extensive post-flight aerodynamic analyses that have been so successfully employed by FM&C during the Shuttle program could be applied to the KMR environment as well.

B.2. Joint KMR / FM&C Shuttle Tracking Sensor Study

The BET methodology described above is also being proposed to support a joint effort between KMR and FM&C analysts. This investigation will include a trajectory reconstruction activity for a selected NASA Space Shuttle mission or, if desired, for a multitude of flights. The study is intended to focus on tracking sensor performance for a variety of complexes that typically support both KMR entry vehicle tests and Shuttle entries terminating at the U.S. West coast. These post-flight analyses will aid in the isolation of various tracking sensor error sources to include, for example, sensor biases, errors in surveyed location, and timing ambiguities.

Readers should note that an integral part of this activity will be the close coordination between FM&C and the various participating DoD and NASA agencies. This planning phase will have to account for changes in the Space Shuttle mission timeline(s) and accommodate contingency modes of operation as well. For example, the planned Shuttle entry date may be delayed due to inclement weather at the landing site and, as a result, participants in the joint study will have to react accordingly. It should also be noted that FM&C has developed and maintained professional relationships with both civil service and contractor personnel throughout the research community during our ongoing Space Shuttle BET activities. These established interfaces include, but are not limited to, the acquisition of TDRSS data and additional support provided by colleagues at the NASA Goddard Space Flight Center (GSFC), delivery of recorded on-board Shuttle dynamic data and C-band tracking measurements via JSC, and acquisition of cinetheodolite camera tracking data during the Shuttle landing and rollout phase at Edwards Air Force Base (EAFB). It is felt that these current relationships will be of invaluable assistance when planning and executing the proposed joint Shuttle activity.

The post-flight BET for a selected Shuttle mission will be generated during the reentry phase from approximately entry interface (EI), at 122 km, throughout landing and rollout on the runway. A representative Space Shuttle ground track for a West coast entry is shown in Figure 10. Also included in this figure is a sample of the tracking coverage that would be available for this type of entry. Note the vast array, though still limited for simplicity, of coastal radars that support the final descent phase. These same tracking complexes might also support the launch of a KMR reentry vehicle and, in a similar fashion, the Hawaii and Kwajalein locations as shown in the figure would provide coverage for the mid-range and terminal regions, respectively. Moreover, the Shuttle ground track as shown in Figure 10 is very similar in nature to a typical KMR entry vehicle ground track. Finally, readers should note the TDRS-1 location annotated on the figure. This corresponds to the geosynchronous relay satellite of the TDRSS that was available for Shuttle support during this entry. As mentioned earlier, FM&C possesses the unique capability to process these data for reentry trajectory reconstruction. In fact, the TDRS-1 data (2-way Doppler observations) for this particular Shuttle mission were implemented during generation of the post-flight BET.

Figure 11 presents the corresponding altitude profile for the Space Shuttle entry discussed above. Here, the altitude (in km) is plotted versus time from the chosen epoch in seconds, in this case corresponding to approximately 155 km. Also annotated on the figure are tracking timelines for a variety of sensors supporting this particular Shuttle entry. Again, note the coverage provided by the Kwajalein sensor (KMAC) around EI, and the mid-range tracking associated with the Hawaiian KPTC complex. The terminal region at the West coast landing site was supported by numerous tracking sensors as shown. Included here are sensors from the Point Mugu (PMFC), San Nicholas Island (SNFC), Point Pillar (PTPC), Vandenberg Air Force Base (VAFB), and NASA Dryden Flight Research Center (DFRC) complexes. Additionally, except during a short period of time due to an abrubt Shuttle attitude maneuver, the TDRS-1 relay satellite provided tracking coverage throughout gaps between the various Kwajalein, Hawaii, and West coast sensors. As a result, the TDRS-1 tracking observations provided an excellent source of data for an overall credibility check of the final post-flight BET.

For completeness, Table 5 is presented herein as a summary of the various tracking sensor complexes available for support of a Space Shuttle entry and landing phase at the U.S. West coast. These radar locations are currently part of the NASA Ground Spacecraft Tracking and Data Network (GSTDN). Again, readers are reminded that C-band tracking for Shuttle is only provided via skin tracking and does not accommodate beacon coverage. As indicated by the locations of these complexes, the same tracking sensors that support a Shuttle entry may conceivably be identical to those of a KMR entry vehicle test in the lauch, mid-range, and impact regions. It is recognized, though, that numerous other sensors are available for KMR support as previously indicated by Table 3 during the database discussions. Included here are the various C-band, RADOT, and ballistic camera tracking sensors. It is the intent

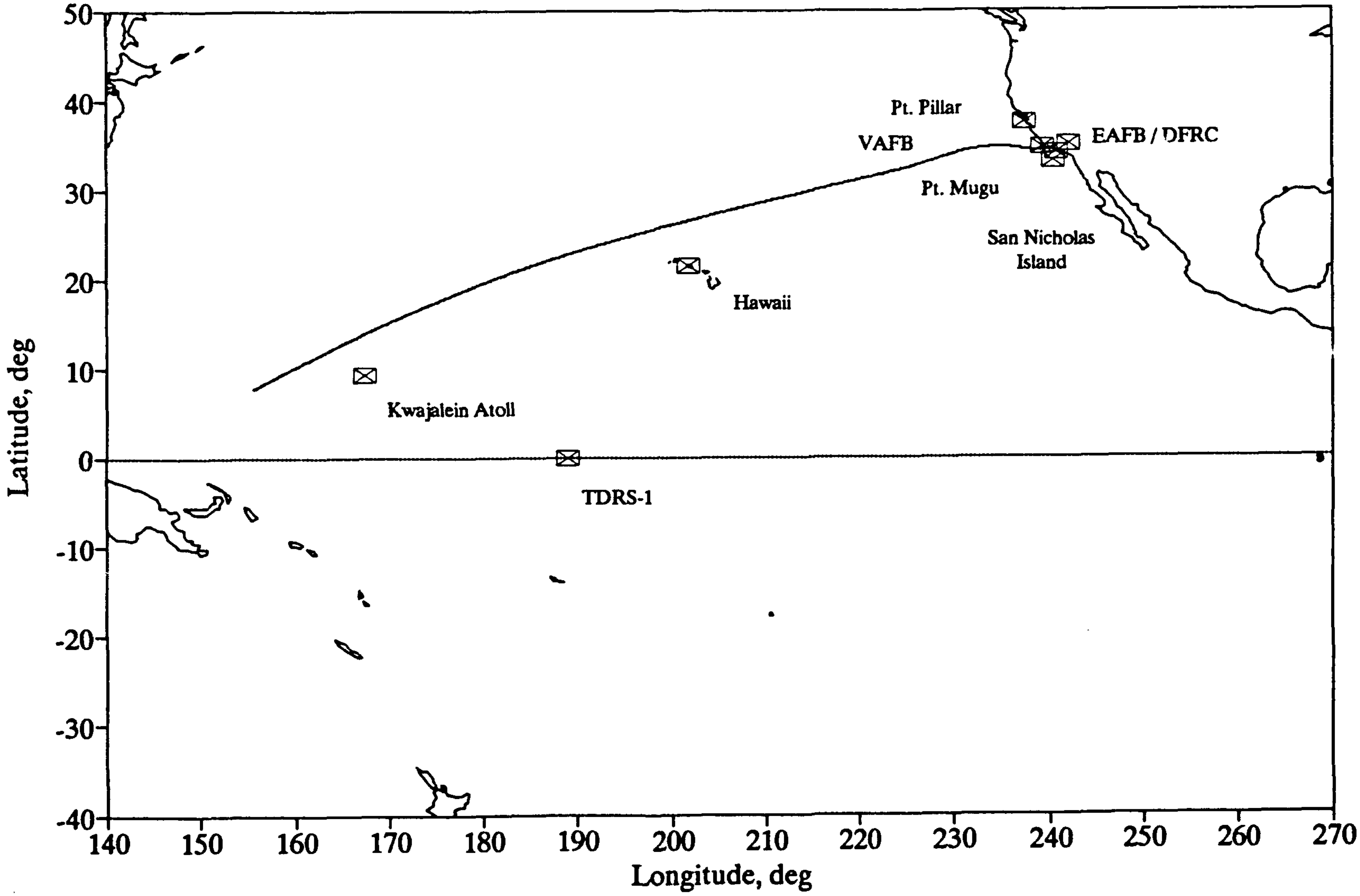

Figure 10. Representative Space Shuttle Entry Ground Track and Metric Tracking Coverage

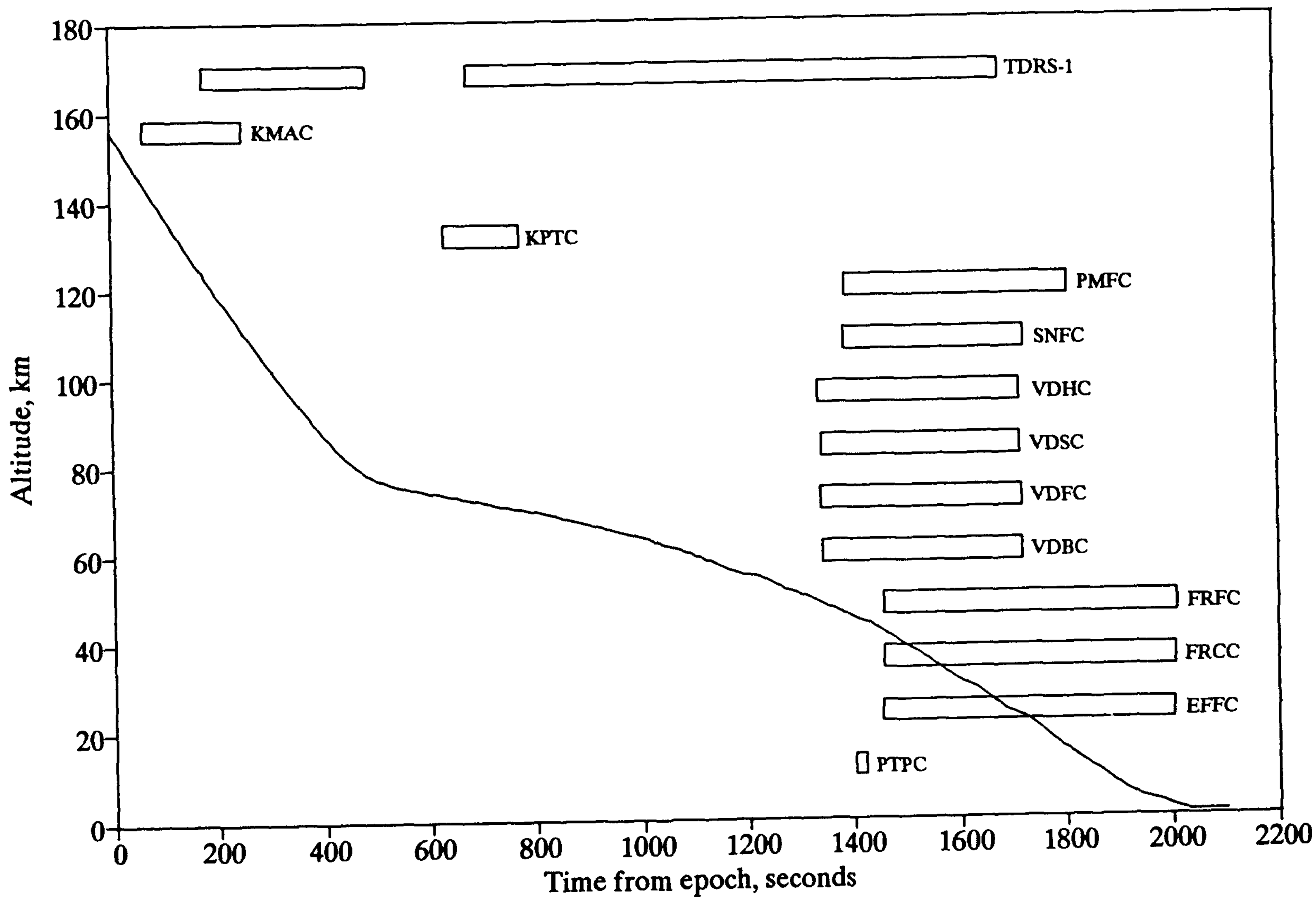

Figure 11. Representative Shuttle Altitude Profile and Tracking Timelines

STATION	RADAR	LOCATION
EAFC	FPS-16	Edwards AFB, California
EFFC	FPS-16	Edwards AFB, California
FRCC	FPS-16	NASA Dryden Flight Research Center
KMAC	ALTAIR	Kwajalein Atoll (P-band)
KMLC	ALTAIR	Kwajalein Atoll (P-band)
KMRC	ALCOR	Kwajalein Atoll (C-band)
KMTC	FPQ-19	Kwajalein Atoll (C-band)
KPTC	FPQ-14	Kaena Point, Hawaii
PMFC	FPS-16	Point Mugu, California
PMPC	FPS-16	Point Mugu, California
PMSC	FPS-16	Point Mugu, California
PPMC	MPS-36	Point Pillar, California
PTPC	FPQ-6	Point Pillar, California
SNFC	FPS-16	San Nicholas Island
SNIC	FPS-16	San Nicholas Island
SNSC	FPS-16	San Nicholas Island
VDBC	TPQ-18	Vandenburg AFB, California
VDFC	FPS-16	Vandenburg AFB, California
VDHC	HAIR	Vandenburg AFB, California
VDSC	FPS-16	Vandenburg AFB, California

Table 5. Kwajalein, Mid-Range, and Coastal Radars Typically Available for Space Shuttle Entry Support

of this proposed KMR/FM&C joint tracking sensor study to activate these additional DoD sensors in order to support a Space Shuttle entry or entries. This additional support, of course, would supplement the normal coverage provided by the GSTDN and would include the TDRSS as well.

The resulting post-flight analyses would encompass the generation of several BETs for a single Shuttle entry. These BETs would include one generated from the GSTDN observations only, a similar trajectory utilizing only the DoD sensors, and, lastly, a joint BET where all sensors (both GSTDN and DoD) are employed. An extensive study would then follow where trajectory and observation residual comparisons would be performed. Additionally, sensor bias estimates as well as surveyed sensor locations could be accumulated, adjusted as necessary, and further analyzed. These post-flight Shuttle studies would be very similar to the database analyses for KMR entry vehicle tests as presented earlier. Moreover, by including several Space Shuttle entries in these investigations, a statistical ensemble of BET differences and sensor performance parameters could also be accumulated. These results would provide KMR analysts with a comprehensive assessment of tracking sensor performance throughout a typical reentry vehicle trajectory profile.

The implementation of the FM&C BET methodology for both KMR entry vehicle support and the joint Space Shuttle tracking sensor study necessarily implies the availability of a secure computing facility for these activities. Currently, the ENTREE software and associated BET utilities are resident on Control Data Corporation (CDC) CYBER mainframe computers at NASA LaRC under the Network Operating System (NOS). As part of this proposed effort, secured computing facilities that are commensurate with the security requirements associated with these BET investigations will be provided as GFE. The ENTREE program and supporting software utilities will be made resident on these GFE computers and accessed by FM&C analysts via secure datalines. Finally, the necessary modifications and checkout to enable use of same will be performed by FM&C.

IV. SUMMARY AND CONCLUSIONS

This report has proposed and demonstrated the feasibility of several methods to assess the post-flight BET results generated for reentry vehicle tests at Kwajalein. Included here are the compilation of historical and future BET data into a database system, the implementation of the FM&C BET methodology in support of a limited set of subsequent KMR tests, and, finally, a proposed FM&C/USASDC joint Space Shuttle tracking sensor study. These methods will be utilized to investigate the various complex aerodynamic and atmospheric issues associated with atmospheric reentry vehicles.

The BET database will consist of a variety of information to include available post-flight BET results and other ancillary data. The latter includes data from external radar and optical tracking sites, KMR atmospheric models and measurements, on-board sensor measurements (if available), and, finally, pre-flight estimates of vehicle aerodynamic coefficients. This knowledge base will allow FM&C analysts to perform extensive statistical aerodynamic and atmospheric analyses from an ensemble of BET results generated via a multitude of KMR entry vehicle tests. An example of such analyses has been presented for lift and drag coefficient, as well as lift-to-drag ratio, comparisons between a representative NASA Space Shuttle entry and statistical results compiled from a series of twenty-two (22) earlier Shuttle missions. It is proposed that similar investigations can be implemented in support of entry vehicles in the KMR environment to enhance future aerodynamic (and atmospheric) modeling.

The FM&C BET generation methodology has also been recommended for additional post-flight BET analyses of KMR entry vehicles. A requirement for this process is a source of inertial quality vehicle dynamic data. Hence, an inertial BET is generated rendering the entire process as *atmospheric independent*. Here, a more accurate trajectory estimate is produced whereby atmospheric effects are accommodated as an additional post-processing activity. The FM&C-generated BET will provide another valuable source of post-flight results to be included in the database analyses described above.

Finally, the FM&C methodology will be the primary contributor of BET data for a proposed joint Shuttle trajectory reconstruction activity with KMR analysts. Here, radar and optical tracking sensors that support KMR entry vehicle tests will supplement the normal Space Shuttle tracking coverage provided by NASA via the GSTDN. It is recommended that a series of Shuttle entries be supported in this manner in order to provide an ensemble of BET results. Thus, an extensive KMR tracking sensor assessment can be performed to isolate such error sources as sensor biases, inaccurate surveyed sensor locations, and timing ambiguities.

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